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Formation Process of Magnetized Fusion Target on the YingGuang 1 Device *

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Magnetized target fusion is an alternative method to fulfill the goal of controlled fusion, which combines advantages of both magnetic confinement fusion and inertial confinement fusion since its parameter space lies between the two traditional ways. Field reversed configuration (FRC) is a good candidate of magnetized targets due to its translatable, compressible, high β and high energy density properties. Dynamic formation process of high density FRC is observed on the YingGuang 1 device for the first time in China. The evolution of a magnetic field is detected with magnetic probes, and the compression process can be clearly seen from images taken with a high-speed multi-frame CCD camera. The process is also studied with two-dimensional magneto hydrodynamic code MPF-2D theoretically, and the results agree well with the experiment. Combining the experimental data and the theoretical analysis, the length of the formed FRC is about 39 cm, the diameter is about 2–2.7 cm, the average density is 1.3×10^{16} cm^{-3}, and the average temperature is 137 eV.

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Scientists have already worked on fusion for more than half a century. Two traditional fusion approaches, magnetic confinement fusion (MCF) and inertial confinement fusion (ICF), have made significant achievements in recent years, which give researchers a great encouragement. For instance, experiment of ICF on national ignition facility (NIF) achieved unity fuel gain in 2014,[1] and the condition of MCF is at the same level.[2] However, for the goal of commercial application, there are still more important and difficult works needed. Due to huge facilities and large costs of two traditional ways, researchers proposed several new type facilities, which are compact and economical, such as FRCHX at the Air Force Research Laboratory (AFRL),[3] MagLIF at Sandia National Laboratory,[4] CFR at Lockheed Martin Company,[5] C-2 at Tri Alpha Energy Company.[6] Most of the new approaches proposed recently belong to the concept of magnetized target fusion (MTF).

In fact, MTF was proposed more than 30 y ago,[7,8] which is an approach to fusion with plasma parameter space between MCF and ICF in scales of time and density.[9,10] Inherent features of field reversed configuration (FRC) make it a good candidate for magnetized target. FRC[11,12] is a kind of compact toroid with very simple topology, which has closed poloidal magnetic field without toroidal field. It is translatable and compressible, which makes it possible to isolate the region of formation and compression. High β and high energy density properties of FRC are very important for the design of a compact reactor.

AFRL collaborated with Los Alamos National Laboratory (LANL) for many years on MTF, which could be separated into three steps: formation of target plasma, translation of target plasma into target chamber, and compression of the chamber along with the plasma to fusion conditions.[13] For the formation step, high density plasma target was achieved on FRX-L at LANL with density $n \approx 5\times10^{16}$ cm^{-3}, temperature $\langle T_e + T_i \rangle \geq 300$ eV, and $\beta \sim 0.9$.[14] To test translation, capture, and compression of FRC, a new machine called field reversed compression and heating experiment (FRCHX) was built at AFRL, which includes an aluminum liner for implosion onto trapped FRC. It was demonstrated that the aluminum liner could already trap high density FRC within 14 μs. However, it is still a short life time compared with the required implosion time 25 μs.[3]

Tri Alpha Energy Company found a new way to form stable FRC with C-2.[15] By taking the collision-merging technique, long-lived FRC was achieved by colliding and merging two hot FRCs. It was reported that FRC in C-2 could last for 5 ms.[16] However, unlike high density FRC in FRX-L and FRCHX, the density of FRC in C-2 is quite small $\sim4\times10^{13}$ cm^{-3}.[6]

In China, construction of the YingGuang 1 device[17] was completed in 2014, which aims at carrying out research on formation and confinement properties of magnetized plasma target. The designed values of peak reversed current and magnetic field of this device are 1.5 MA and 4 T, respectively, with rise time of 3 μs.[17] In addition, YingGuang 1 may also be used to study collisionless shock waves, magnetic reconnection and instability of plasma.

The main part of the YingGuang 1 device is the theta coil (see Fig. 1(a)), which is composed of eight 5-cm-long single turn coils with seven 1-cm gaps among them, and the inner diameter is 21 cm. The vacuum chamber is a quartz tube inside the theta coil, whose outer diameter is 14 cm and inner diameter is 12.5 cm.

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During FRC formation experiments, 8 Pa argon gas filled the tube.

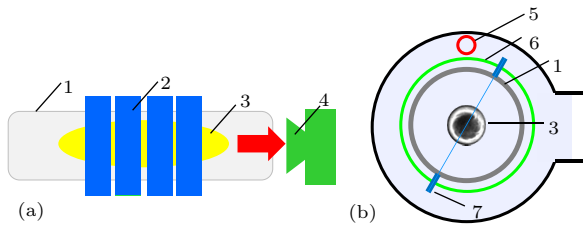

Fig. 1. Cross sections of theta coil with diagnostics in the R–Z plane (a) and the R–θ plane (b). The system is composed of (1) quartz tube, (2) single-turn theta coil, (3) plasma target, (4) high-speed multi-frame CCD camera, (5) B-dot probes, (6) flux loops, and (7) laser interferometer.

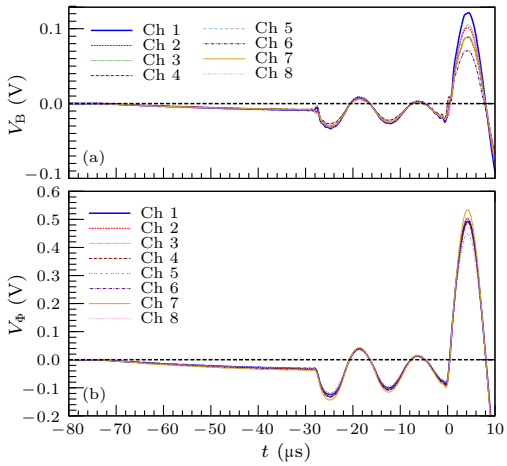

Fig. 2. (Color online) Signals detected with 8 B-dot probes (a) and 8 flux loops (b) for shot 150716-02. The main capacitor bank triggered time is set to be $t = 0$.

Diagnostics of YingGuang 1 consists of B-dot probes (B_z), flux loops and a high-speed multi-frame CCD camera. Eight B-dot probes and eight flux loops are placed at the same axial positions just outside quartz tube, which are used to detect external magnetic field and flux inside, respectively (see Fig. 1(b)). Signals of B-dot probes and flux loops are recorded by oscilloscope through a circuit integration module with sampling rate of 625 MHz. At the end of the quartz tube, an 8-frame camera is used to take visible axial images during the formation process. The high speed camera is produced by Institute Of Fluid Physics, China Academy Of Engineering Physics, and the resolution is 1600 × 1200 with the highest rate of 200 million frames/second. For shots 150910-01 and 150910-02, the exposure is 20 ns for each frame at a rate of 2 million frames/second.

Discharge order of cusp, bias, ionization and main capacitor banks is controlled by a delayed synchro device. In Fig. 2, signals of B-dot probes and flux loops are illustrated for shot 150716-02. External magnetic field could be obtained roughly by multiplying the coefficient of 14.4 T/V and the signal of B-dot probe. The main capacitor bank triggered time is set to be $t = 0$. The cusp bank is triggered first at $t = -518$ μs, which generates the cusp field at the end of theta coil. Then, the bias bank is triggered at $t = -78$ μs, which produces slowly varying magnetic field (inverse to the cusp field). At $t = -28$ μs, pre-ionization bank is fired to ionize 8 Pa Argon gas inside quartz tube, and the bias field is embedded inside the plasma. Finally, the main bank is triggered, which produces a large reversed magnetic field in comparison with the bias field.

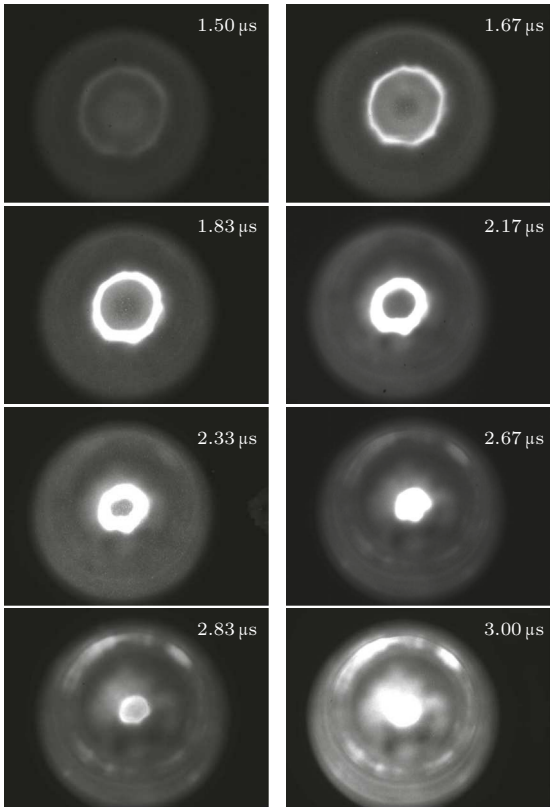

Fig. 3. Images taken with a high-speed multi-frame CCD camera during plasma compression of shot 150911-03.

In Fig. 3, eight visible light images of shot 150911-03 are illustrated, from which the compression process can be clearly seen. As the main field bank is triggered, plasma is compressed with a large magnetic pressure, and the temperature will increase. Due to the screening effect of plasma, it is not easy for the main field to diffuse inside deeply, and a bright torus is formed at the surface of plasma, which could be seen in Fig. 3. With the main field becoming stronger, the plasma torus becomes brighter and thicker. At $t = 2.83$ μs, plasma reaches peak compression with the smallest radius, which is about 1 cm for shot 150911-03. After that, plasma will shrink axially and will expand radially due to Lorentz force.

To have a better understanding and to obtain more details of experiment, theoretical analysis is certainly needed. In previous works, we introduced the newly developed two-dimensional magneto hydrodynamic code MPF-2D,[18] for which the arbitrary Lagrangian–Eulerian method is used to solve the equations. It is demonstrated that MPF-2D could give

a good description for the formation process of field reversed configuration,[18,19] and critical factors for translation process[20] are also studied with such a code.

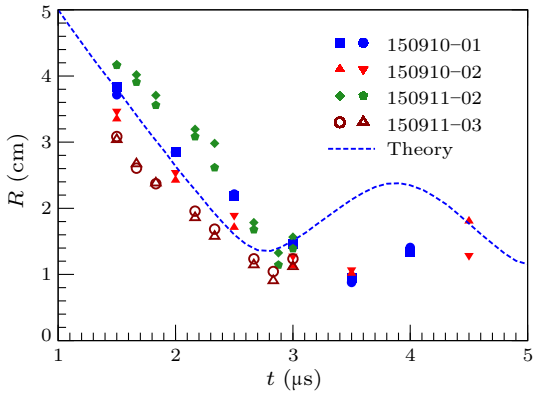

Fig. 4. Evolution of separatrix radius calculated theoretically compared with the experimental data. For each shot, the radii of both horizontal and vertical directions are measured. Blue square and disk refer to shot 150910-01, red solid up and down triangles refer to shot 150910-02, green diamond and pentagon refer to shot 150911-02, brown open circle and triangle refer to shot 150911-03.

MPF-2D could not describe ionization of the gas, thus the simulation is started from the time when the main capacitor bank is fired, at which time argon gas is assumed to be fully ionized. With data detected by B-dot probes and flux loops, bias field, cusp field and main field for simulation are set to be 0.1 T, −1.2 T and −0.9 T, respectively. Quarter cycle times of bias bank and cusp bank are 70 μs and 500 μs, which are sufficiently large compared with 4 μs quarter cycle time of the main bank. Therefore, they could be considered as constant fields. Initial density is set to be 2×10^{15} cm^{-3}, which corresponds to 8 Pa argon gas filling the quartz tube.

The comparison of separatrix radius calculated theoretically and experimental data is plotted in Fig. 4. The results of shots 150910-01, 150910-02, 150911-02 and 150911-03 are presented. For each shot, the radii of both horizontal and vertical directions are measured from images taken with a high-speed multi-frame CCD camera. The blue dashed line refers to the calculated separatrix radius, which is defined as the radius of cross section with zero magnetic flux. From our calculation, radius at $t = 1$ μs is 5.00 cm, and it decreases almost linearly due to the large magnetic pressure caused by the main field. At $t = 2.8$ μs, the outer and inner pressures are balanced at radial directions, and the peak compression is reached with smallest radius 1.36 cm. The length of FRC is about 39 cm at peak compression. Then, the shrinking effect of plasma in axial direction due to Lorentz force will lead to radial expansion. The theoretical result is consistent with experimental data in the compression process. The calculated peak compression time 2.8 μs also agrees well with that of shots 150911-02 and 150911-03, which are 2.87 μs and 2.83 μs, respectively. For shots 150910-01 and 150910-02, the peak compression comes out at 3.5 μs, which comes later than our calculation. The reason is that our simulation is focused on shot 150911-03, which gives nice pictures of the compression process as shown in Fig. 3. By theoretical analysis, we find that the initial density is very sensitive to the peak compression time, and this should be the main reason causing such a difference.

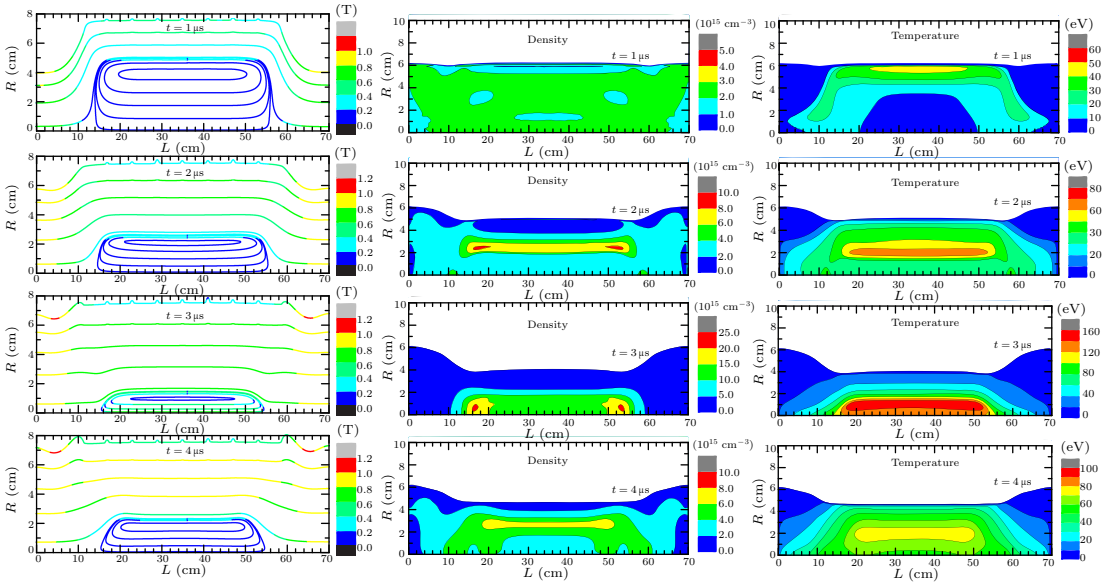

Fig. 5. Evolution of magnetic filed, density and temperature calculated with the two-dimensional magneto hydrodynamical method.

Evolution of magnetic field, density and temperature during the formation process are plotted in two dimensions as shown in Fig. 5. Since YingGuang 1 is cylindrical, only half part of the R–Z plane is calculated. Due to the cusp coil, gradient of the magnetic field is very large at the end of the theta coil,

which promotes complete magnetic reconnection in a very short time (about 0.5 μs here), and then FRC is formed. After that, FRC is compressed with the main field. At the beginning of FRC being formed, the embedded magnetic field is just initial bias field with the value of 0.1 T. During the compression, the magnetic field embedded inside FRC becomes larger and larger, which rises up to 0.63 T near the symmetry axis at $t = 3.0\,\mu$s. Due to the expansion in radial direction discussed above, the magnetic field reduces to 0.13 T near the symmetry axis at $t = 4.0\,\mu$s.

The middle column of Fig. 5 gives the evolution of density. With compression, the density increases quickly. At $t = 2.0\,\mu$s, two dense spots are formed at the end of FRC with density about $8.3\times10^{15}\,\mathrm{cm}^{-3}$. At $t = 3.0\,\mu$s, the maximum density of FRC reaches $2.1\times10^{16}\,\mathrm{cm}^{-3}$, and the average density is $1.3\times10^{16}\,\mathrm{cm}^{-3}$. At $t = 4.0\,\mu$s, with radial expansion and plasma diffusion, the dense spot vanishes and average density reduces to $4.6\times10^{15}\,\mathrm{cm}^{-3}$.

For evolution of temperature, there is no hot spot though a hot zone formed during compression. This is mainly caused by Joule heating and the work of pdV. Comparing figures of magnetic field and temperature in Fig. 5, it shows that the hot zone nearly coincides with the magnetic null zone, where the magnetic field is quite small. Plasma temperature rises monotonically up to 137 eV at $t = 3.0\,\mu$s with the highest part 144 eV. The highest temperature is very close to the average temperature due to large volume of hot zone. Then, the temperature reduces quickly to 70 eV at $t = 4.0\,\mu$s with plasma expansion.

In summary, high density FRC has been observed for the first time in China, which is an important progress on the YingGuang 1 device and also a good start point for research on MTF. The dynamic compression process could be clearly seen from images taken with a high-speed multi-frame CCD camera. With data detected by B-dot probes and flux loops, a two-dimensional simulation is made towards shot 150911-03 with code MPF-2D. The calculated results agree well with the experimental data on separatrix radius during the compressing process, and it could also give correct time of peak compression (2.8 μs), which are 2.87 μs and 2.83 μs for shots 150911-02 and 150911-03, respectively. According to theoretical results at peak compression, the formed FRC is about 39 cm long and 2.7 cm wide; the average density is about $1.3\times10^{16}\,\mathrm{cm}^{-3}$ with the maximum value of $2.1\times10^{16}\,\mathrm{cm}^{-3}$; and the average plasma temperature is 137 eV. To fulfill controlled fusion with MTF, stable, high-density FRC is needed. In the future, we will try to improve the properties of formed FRC, like density, temperature and lifetime.

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